AD-A050 793 VIRGINIA UNIV CHARLOTTESVILLE RESEARCH LABS FOR THE--ETC F/G 13/9
HIGH SPEED ROTOR BALANCING.(U)
FEB 77 W D PILKEY DAAG29-75-G-0055
UNCLASSIFIED UVA/525037/MAE78/101 ARO-12515.6-E NL

1 OF 1
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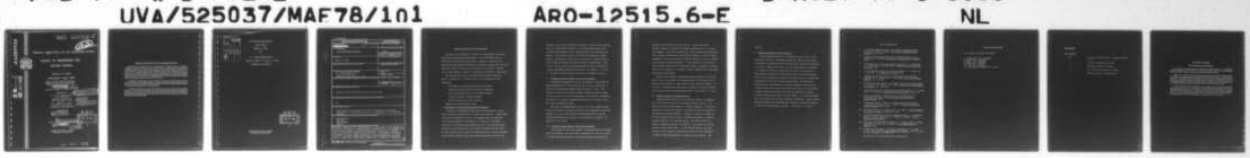

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RESEARCH LABORATORIES FOR THE ENGINEERING SCIENCES

SCHOOL OF ENGINEERING AND

APPLIED SCIENCE

University of Virginia

Charlottesville, Virginia 22901

6 HIGH SPEED ROTOR BALANCING.

9 Final Report,

DAAG-29-
Grant No. DAAG29 75 G 0055; 77 G 0027

15 DAAG29-75-G-0055,
DAAG29-77-G-0027

Submitted to:

U. S. Army Research Office
P. O. Box 12211
Research Triangle Park
North Carolina, 27709

18 ARO

Attn: DRXRO-IP-L-12515-E
Richard O. Ulsh, Chief
Information Processing Office

19 12515.6-E

Submitted by:

10 W. D. Pilkey

14 Report No. UVA/525037/MAE78/101

11 Feb [redacted] 77

12 10p.

APPROVED FOR PUBLIC RELEASE:
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HIGH SPEED ROTOR BALANCING

FINAL REPORT

WALTER D. PILKEY

1977

U. S. ARMY RESEARCH OFFICE

GRANT NO. DAAG29 75 G 0055; 77 G 0027

UNIVERSITY OF VIRGINIA

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

[redacted]

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

HIGH SPEED ROTOR BALANCING

5. TYPE OF REPORT & PERIOD COVERED

Final

6. PERFORMING ORG. REPORT NUMBER

DAAG29 75 G 0055, 77 G 0027

7. AUTHOR(s)

Walter D. Pilkey

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

U. S. Army Research Office
Post Office Box 12211
Research Triangle Park, NC 27709

12. REPORT DATE

1977

13. NUMBER OF PAGES

9

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Rotating Shaft
Balancing
Rotor Dynamics
Dynamics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the accomplishments of a study exploring new methods for balancing, analyzing and designing flexible rotating shafts. It is assumed that the balancing problem is an identification/optimization problem. Emphasis is given to computational optimization formulations. In addition to balancing techniques, an optimal design procedure for rotor bearing systems is proposed. Also, modal and direct integration transient analysis methods are developed. Finally, a numerically stable analysis approach is formulated and implemented.

PROBLEM STATEMENT AND ACCOMPLISHMENTS

The goal of the program is to explore new techniques for balancing, analyzing, and designing rotating shafts. This study began with the assumptions that the balancing problem is rightfully classified as an identification/optimization problem and that modern computational techniques hold great promise in aiding in the solution of the problem. Throughout the study emphasis is given to computational optimization formulations.

The achievements of this study, which was performed during the period 21 October 1974 - 20 October 1977, can be grouped into five categories:

Development of Computational Balancing Techniques

Sensitivity Study of Rotors to Errors in Balancing

Efficient Optimal Design of Rotor Bearing Systems

Transient Analysis of Rotating Shafts

Numerical Stability of Rotor Analyses

These efforts are summarized below.

I. Development of Computational Balancing Techniques

A variety of computational methods have been developed for identifying the unbalance deflection of a flexible rotating shaft. These differ from previous techniques in that the new methods permit the magnitude of the balance weights to be controlled. In addition to permitting regulation of the balance weight magnitudes, one of the approaches leads to balance weights that reduce rotor runouts at speeds above the level at which the shaft can be safely run without balancing. Another technique selects balance weights of the least possible magnitude and thereby can

sometimes avoid stress concentration problems. The most recent development is a method that in addition to selecting balance weights also finds the optimum axial location (balance planes) for positioning the weights. This method is based on an iterative computational scheme. Numerical simulations indicate that the technique is indeed effective. Most of these new methods are highly efficient computationally. This is due to the fact that the balancing problem can often be handled as a linear programming identification problem. See papers 1, 2, 8, and 9. The optimal balancing plane work has not yet appeared in print.

II. Sensitivity Study of Rotors to Errors in Balancing

A method was developed for solving the problem of determining the maximum deflection of a shaft resulting from the worst combination of errors in placing balance weights along the axis of a rotor. This analysis, called a worst balance analysis, provides an index of sensitivity of the rotor to errors in balancing. The solution is formulated in general as a nonlinear programming problem and in particular cases as a linear programming problem.

This work is extended beyond rotors in the form of response bound analyses for elastic and plastic structures with incompletely prescribed loading. As in the case of shafts, these analyses serve to provide sensitivity measures for structures to uncertainties in loading. See papers 3, 4, 5, 7 and 8.

III. Efficient Optimal Design of Rotor Bearing Systems

A new method for the optimal design of bearing systems was developed. With the new method, the conventional (automated) trial and error search for optimal parameter values for a prescribed design configuration is

replaced by an efficient two-stage process. In the first stage absolute optimum (or limiting) performance characteristics of the shaft are computed. In the second stage using a chosen bearing system configuration, parameter identification techniques are applied to find the design parameters so that the suspension system will respond as close as possible to the absolute optimal performance. In this approach, the repetitive shaft analyses required in the conventional search techniques are avoided. Hence, the new technique is extremely efficient computationally and appears suitable for large systems.

Another less efficient, computational design technique is also proposed. This is a procedure for designing shafts or structures to be as insensitive as possible to uncertainties in the loading environment. In the case of rotating shafts this means the design is relatively insensitive to errors made in placing balance weights. See papers 5,6,7, and 8.

IV. Transient Analysis of Rotating Shafts

A general modal solution for the transient response is formulated for a rotating shaft subjected to arbitrary loading functions. The shaft can be modeled with lumped or continuous parameters. The bearing systems can be arbitrarily complex, containing pedestal mass, bearing and pedestal springs and dampers. Transient or aperiodic loadings can be placed anywhere along the shaft, including displacement or velocity inputs at the base of the bearing systems. This would permit, for example, earthquake motions to be simulated. The formulation involves the sum of complex mode shapes. As an additional benefit the rotor stability can be studied by observing the behavior of the eigenvalues. A computer program implementing the formulation was prepared. See

paper 11.

V. Numerical Stability of Rotor Analyses

A long-standing problem in rotor dynamics is that the use of the relatively efficient line-solution method, the transfer matrix method, for analyses is encumbered by the grave problem of numerical inaccuracies as soon as a complex rotor model, e.g. many lumped masses, is employed or a difficult problem, e.g. high critical speed, is to be solved. A new technique, the Riccati transfer matrix method, has been developed which not only eliminates the numerical instabilities but is about twice as efficient as the usual transfer matrix method. The method which employs Riccati transformations (Invariant Imbedding) still makes use of the existing large catalogs of transfer matrices for rotating shafts. A computer program using this method for the computation of damped critical speeds and mode shapes has been prepared. The program includes some novel methods for efficient eigenvalue computations. Another method has been developed for stabilizing the analysis of long shafts resting on stiff but non-rigid support systems. See paper 11, 12, and 13.

LIST OF PUBLICATIONS

1. "A Linear Programming Approach for Balancing Flexible Rotors", R. M. Little and W. D. Pilkey, *The Journal of Engineering for Industry*, Vol. 94, 1976

2. "Constrained Balancing Techniques for Flexible Rotors", W. D. Pilkey and J. T. Bailey, *The Journal of Engineering for Indusrty*, 1978.

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11. "Transient Response of a Rotor in Damped Bearings," J. Strenkowski and W. D. Pilkey, ASME Paper No. 77-DET-21, to appear in *J. of Engineering for Industry*

12. "The Riccati Transfer Matrix Method," G. C. Horner and W. D. Pilkey ASME Paper No. 77-DET-32, to appear in *J. of Engineering for Industry*, 1978.

13. "Complex Infinite Beams on an Elastic Foundation," P. Y. Chang, D. Hsu, and W. Pilkey *J. of the Structural Division*, ASCE, Vol. 103, No. ST11, November, 2277-2282, 1977

Other papers are being considered for publication.

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